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Evaluation of the Impact of Wireless Communication in Production via Factory Digital Twins

Rasmus Suhr Mogensen[1], Ignacio Rodriguez[1], Casper Schou[2], Steffen Mortensen[3], Michael Sparre Sørensen[4]

[1] Wireless Communication Network Section, Department of Electronic Systems, Aalborg University, Denmark, Fredrik Bajers Vej 7A, 9220, Aalborg Øst, Denmark, rsm@es.aau.dk, irl@es.aau.dk
[2] Department of Materials and Production, Aalborg University, Denmark, Fibigerstræde 16, 9220, Aalborg Øst, Denmark, cs@mp.aau.dk
[3] Move2x IVS, Nørresundby, Denmark, Lars Dyrskøts Vej 19, 9400, Nørresundby, Denmark, steffen@move2x.dk
[4] Integrate A/S, Aalborg, Denmark, Gammel Gugvej 17C, 9000, Aalborg, Denmark, mss@integrate.dk

Abstract

This paper investigates the impact of wireless communication in manufacturing systems. By using a digital twin representation of a real production line, a production throughput evaluation is performed for various configurations considering different wireless control communication schemes over Wi-Fi, 4G LTE and 5G NR. The results show that operating the manufacturing execution system (MES) over wireless instead of Ethernet will minimally impact production, as the production throughput will not be degraded for lines containing slow stations; or will only degrade by a maximum of 0.41% during one month of continuous production in the case of fast lines involving quick stations.

I. INTRODUCTION

As factories move towards Industry 4.0, the replacement of control communications based on Ethernet and other wired technologies with wireless becomes a necessary enabler in order to fulfill the envisioned flexibility and easy reconfigurability of the production facilities [1]. Removing cables and providing wireless control of the production does, however, come with an associated cost: currently available technologies such as Wi-Fi (the most widespread wireless technology deployed in factories nowadays) or 4G LTE introduce significantly larger communication delays compared to standard Ethernet [2]. As we reported in [3], the median one-way latency measured in an operational manufacturing execution (MES) system can vary from the 0.09 milliseconds (ms) experienced over Ethernet to 1.40-2.22 ms when operating over Wi-Fi, and to up to 23.8 ms when running over a public 4G connection. While the effect of communication delays in each of the individual modules of the lines appears negligible, their overall effect in the entire production line in the long-term may affect the production outcome.

In order to provide some insight into the long-term effects of the wireless control of the overall production processes, this paper introduces a framework and a methodology for mapping the performance of different wireless technologies to production throughput. For this purpose, we evaluate the efficiency of various production line configurations when operating their MES control over different radio technologies. In particular, we compare the reference production performance achieved over standard Ethernet with those obtained over Wi-Fi, 4G LTE and the novel 5G NR.

The evaluation is performed by means of a digital twin representation of the Aalborg University (AAU) Smart Production Lab FESTO Cyber-Physical (CP) Factory production line [4], [5], which is often used for other manufacturing-related activities such as virtual commissioning [6]. Digital twins are virtual representations of the physical world which, in addition to mirroring of the physical assets, are characterized by considering the real-time data flows, in contrast to a simulation model [7]. They are one of the main enabling technologies of Industry 4.0 [8] and are moving towards a common resource used in production design and manufacturing planning [9]. However, the communication aspects of the production, and especially those of wireless, are typically not considered in these tools. To the best of our knowledge, we are first authors in leveraging digital twins for evaluating or predicting the behaviour of production lines when controlled by wireless technologies.

II. INTEGRATING WIRELESS IN FACTORY DIGITAL TWINS

For our investigation we leverage the digital twin of a FESTO CP Factory production line. However, it should be noted that the framework/methodology presented in the following is applicable to any other factory digital twin setup and communication technologies. For example, the latency distributions provided in this paper could be reused for evaluation over different digital twin layouts. Also, if other latency distributions are available, the production output could be evaluated over those communication schemes instead.

The production system consists of 6 production modules interconnected by conveyor belts which transport the products across the different process stations (2 per module) during their manufacturing cycle. Within the specific considered configuration, the line is set to produce different variants of mock-up phones. An overview of the reference production line composition is displayed in Fig. 1, and a description of the process stations, including their average processing time is provided in Table I. The overall product order as well as the individual actions of each specific station for a given product are controlled by a MES. When the system is operated over wireless, the Ethernet cables between modules are removed, and dedicated wireless interfaces are applied between the MES and the different workcells. A diagram of such implementation is detailed in [3]. The MES control implies that multiple communications between the MES central controller and the stations happen throughout the overall manufacturing process. On average, 5 control messages are exchanged every time a product arrive to a specific station. For further reference, as described in [10], MES control traffic consists of mainly TCP traffic with packets of 67 B of SDU MAC size (including headers) sent with a frequency of 120 ms, on average. Thus, the system should be considered as a low-throughput and low-density deployment.

In the current digital twin implementation, this flow is converted to a discrete event simulation where both station processing time and communication delays are considered. To the best of our knowledge, communication delays are usually not considered in typical digital twin implementations as Ethernet, the reference communication technology used in MES, consistently achieve latencies in the order of 0.1 ms; which can be neglected due to the dominance of the processing times (typically in the order of seconds). However, the latencies experienced in some wireless systems are significantly larger (in the order of a few tens of ms) and thus, it is essential that they are considered in the simulation in order to have a real estimate of the overall impact on the system performance when a wireless technology is chosen to operate the MES.

In our proposed framework, the communication delays, every time there is an exchange of information between a station and the MES controller, are determined by uniform sampling of the empirical MES latency traces obtained over the real FESTO CP Factory production line, which were previously presented in [3]. Fig. 2.a displays the one-way delay MES latency distributions computed over the real-world traces of the line under different communication schemes:

- Ethernet: default MES communication scheme.
- Ideal Wi-Fi: all modules are connected to a dedicated interference-free WiFi channel (this includes the proper isolation from any other rogue and nearby networks), exclusively used for manufacturing control purposes.
- Non-optimized Wi-Fi: all modules are connected to a standard WiFi channel, potentially interfered by other WiFi networks and not dedicated exclusively to production (i.e. regular office or personal use devices are also connected to this channel).
- Private 4G LTE: all modules are connected to a dedicated 4G channel, exclusively used for manufacturing control purposes. A private 4G network differs from the public 4G network in the sense that it is an in-factory dedicated installation that provides better latency performance and security.
- Private 5G NR[1]: all modules are connected to a dedicated 5G channel, exclusively used for manufacturing control purposes. A private 5G network with ultra-reliable low-latency (URLL) support has been specifically designed for supporting industrial applications, achieving latency values close to those achieved over Ethernet, significantly lower than the ones experienced in 4G private networks [11].

III. DIGITAL TWIN SIMULATION SETTINGS

In order to evaluate the impact of wireless MES control in the overall production process, we consider 4 different scenarios with different digital twin layouts (see Fig.1) and simulation settings which are detailed in Table I. These scenarios are used to evaluate the impact of running the MES control over different wireless technologies in terms of degradation in overall production throughput (PT), computed over the simulation of a full month of continuous production (730 hours). This impact is evaluated by comparing the PT achieved over a given wireless technology with the reference PT obtained when the MES operates over standard Ethernet. In order to do that, the absolute difference in number of manufactured products (Δ) and the normalized production throughput (NPT) metric are defined:

$$\Delta\,[\text{products}] = PT_{\text{Wireless}} - PT_{\text{Ethernet}} \tag{1}$$

$$\text{NPT}\,[\%] = \frac{PT_{\text{Wireless}}}{PT_{\text{Ethernet}}} \,.\, 100 \tag{2}$$

IV. PRODUCTION PERFORMANCE RESULTS & DISCUSSION

The digital twin simulation results are presented in Table II for the different test setup scenarios and MES communication technologies. The table includes the monthly PT as well as the NPT for the cases considering wireless technologies. Fig. 2.b illustrates the NPT for the different cases, and together with Fig. 2.a. serves to put in perspective how the choice of particular wireless technology for MES control impacts the overall performance of the manufacturing process.

The results for the reference scenario, LRC, for both capacity load configurations (100% and 70%), indicate that despite the average communication latency for the different wireless technologies are very different from the ones in the reference Ethernet case, this does not appear to affect the overall production throughput (Δ=0 and NPT=100%). This is due to the presence of the robotic cell on the line, which average processing time is quite large and therefore forces some products to wait in a buffer or circulate around the line until they can be processed by the station [10]. A similar effect would be observed, for example, in lines where other types of slow stations (i.e. manual stations) are present, as the bottleneck in this case is the station processing time and not the control communication delay.

The situation changes when no robotic cell is placed in the line. In this case, as the results from the CLL scenario with infinite load capacity describe, we start to observe some impact of the different communication delays over the overall production throughput. Using ideal Wi-Fi, a small decrease of 0.05% is observed with respect to the reference Ethernet case. This difference is higher for the non-optimized Wi-Fi and private 4G LTE cases (0.31% and 0.38%, respectively). For the private 5G case, it is expected that the overall production is comparable to the Ethernet reference case (0.01%), which is much better than the one predicted for the other wireless technologies.

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[1] The private 5G NR latency values have been generated via simulations, but we expect to validate the results once the first release of 5G NR URLL is available in our industrial lab.

Even in the case of faster production lines with high conveyor belt speed and quick stations with short processing time (i.e. camera inspection), as the results from the FLL scenario describe, the impact of wireless control over production remains limited (0.02-0.41%).

Despite the fact that the results presented here relate to a specific production line and configuration, the methodology and observations given in this paper can be generalized to other factory setups with different layouts and production configurations. The simulation presented here considers only continuous production; but real production plans typically include re-configuration of the lines and planned maintenance stops, where the additional benefits of using wireless will be more tangible as service times will be highly reduced due to the fact that no control communication cables between modules will be needed. It is therefore expected that using wireless will result even in positive PT gains when considering the full spectrum of production-related activities including maintenance, reconfiguration, changeover and repairs.

V. CONCLUSIONS

This paper presented an evaluation of the impact of wireless communication technologies on production throughput based on digital twin simulations. The hybrid methodology introduced, which integrated digital twins discrete event simulations and empirical wireless performance, is applicable to any other factory digital twin setup and communication technologies. The study is carried out using different configurations of a digital twin of the CP FESTO Factory production line at the AAU Smart Production Lab, by considering multiple wireless technologies such as Wi-Fi, 4G LTE and 5G NR for the manufacturing execution system (MES) control communication. The production throughput simulation results computed over a full month of continuous production, indicate that the effects of operating the control of production lines over wireless are negligible in the case that slow stations such as robotic or manual cells are present. If no slow stations are present, the wireless MES control can degrade the overall production output by 0.01-0.41% with respect to the standard reference operation over Ethernet, depending on the exact operational configuration of the line and the wireless technology chosen. The results also reveal that 5G NR is expected to provide comparable production performance as the reference one achieved over Ethernet.

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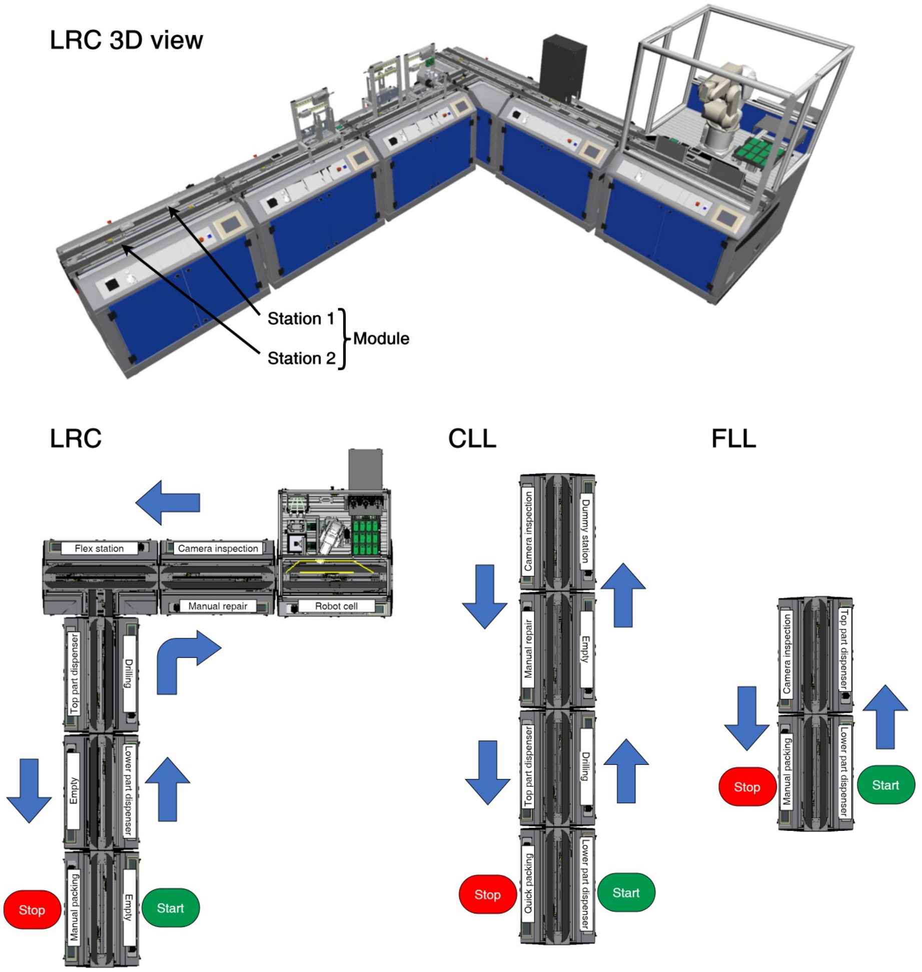

Fig. 1. Overview of reference composition of the digital twin of the AAU Smart Production Lab FESTO CP Factory (3D-view), and 2D-view of the 3 different layouts used in the simulations: line with robotic cell (LRC), closed loop line (CLL), and fast loop line (FLL). The 2D-views depict the overall production cycles, including the specific order of operations and actions performed at each station.

TABLE I
DIGITAL TWIN SCENARIOS AND SIMULATION SETTINGS.

Scenario	Station action (avg. process time)	Conveyor speed	Load capacity	Additional notes
Line with robotic cell (LRC,100%)	Lower part dispenser (5 s) Drilling station (6 s) Manual repair (10 s) **Robotic cell (80 s)** Camera inspection (0.66 s) Flex station (10 s) Top part dispenser (5 s) Manual packing (11 s)	0.1 m/s	100% capacity 16 pallets	Reference configuration. New product orders placed according to real-world intervals. Product type: mixture of mockup phones with different colors. Max. # of simultaneous products being produced = # pallets.
Line with robotic cell (LRC,70%)			70% capacity 16 pallets	New product orders placed at 30% reduced rate compared to LRC,100%
Closed loop line (CLL)	Lower part dispenser (5 s) Drilling station (6 s) Manual repair (10 s) **Dummy station (11 s)** Camera inspection (0.66 s) Flex station (10 s) Top part dispenser (5 s) Manual packing (11 s)	0.1 m/s	∞ capacity 16 pallets	Robotic cell is replaced with a dummy station. New product orders are placed instantaneously once a pallet is free.
Fast loop line (FLL)	Lower part dispenser **(0.66 s)** Top part dispenser **(0.66 s)** Camera inspection **(0.66 s)** Quick packing **(0.66 s)**	**1 m/s**	∞ capacity	Fast-processing production line with fast conveyor belt speed and infinite capacity.

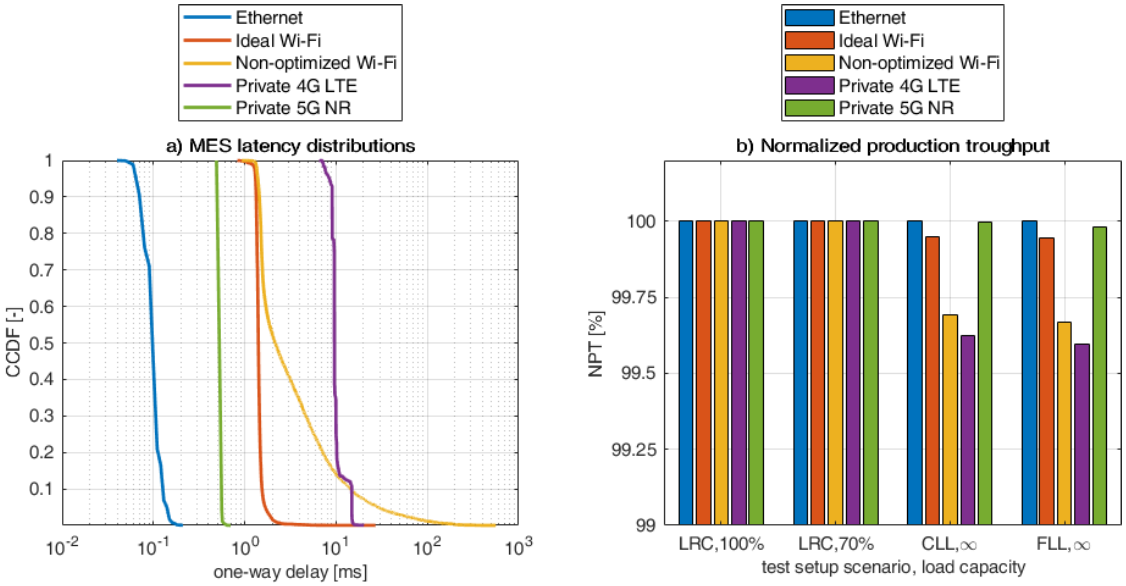

Fig. 2. a) Complementary cumulative distribution function (CCDF) of the MES latency for the different communication technologies used in the study (Ethernet, ideal Wi-Fi, non-optimized Wi-Fi and private 4G LTE are empirical, while the private 5G NR is simulation-based). b) Normalized throughput simulation results for the different test setups and technologies.

TABLE II
ONE-MONTH PRODUCTION THROUGHPUT RESULTS FOR THE DIFFERENT TEST SETUPS AND TECHNOLOGIES.

Technology	Metric	Line with robotic cell (LRC)		Close loop line (CLL)	Fast loop line (FLL)
		100% capacity	70% capacity	∞ capacity	∞ capacity
Ethernet	# manufactured products NTP [%]	29842 100	22834 100	206999 100	847619 100
Ideal Wi-Fi	# manufactured products (Δ) NTP [%]	29842 (=) 100	22834 (=) 100	206894 (-105) 99.949	847153 (-466) 99.945
Non-optimized Wi-Fi	# manufactured products (Δ) NTP [%]	29842 (=) 100	22834 (=) 100	206364 (-635) 99.693	844791 (-2828) 99.666
Private 4G LTE	# manufactured products (Δ) NTP [%]	29842 (=) 100	22834 (=) 100	206221 (-778) 99.624	844184 (-3435) 99.595
Private 5G NR	# manufactured products (Δ) NTP [%]	29842 (=) 100	22834 (=) 100	206995 (-4) 99.998	847464 (-155) 99.982